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Enhanced spontaneous emission from GaAs quantum wells in monolithic microcavities

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Enhanced spontaneous emission has been observed with wavelength-sized monolithic Fabry-Perot cavities containing GaAs quantum wells. With an on-resonance cavity structure, the photoluminescence intensity increases in the cavity axis direction, and the spontaneous emission lifetime is experimentally found to decrease.

Following the recent reports of altered spontaneous emission in optical cavities,[1] attention has turned to utilizing this effect in semiconductor optical devices. For example, the utilization of inhibited spontaneous emission has been proposed to create diode lasers having extremely low threshold current.[2] It has also been recently reported that the spontaneous emission rate of optically thin GaAs/AlGaAs double heterostructures depends on substrate materials.[3] However, until now, there have been few studies of optical cavity effects on semiconductors, possibly because of the difficulty of fabricating the appropriate cavity structures with these materials. For broad emission bandwidth semiconductors, the spontaneous emission rate change can be observed only when the dimensions of the cavity are on the order of a wavelength, in contrast to atomic beam experiments.[4] In this letter we report two experiments designed to detect enhanced spontaneous emission from a semiconductor multiple quantum well (MQW) sample embedded in a monolithic microcavity. In the first experiment, the enhancement is detected as an increase in the spectrally integrated photoluminescence (PL) intensity emitted from the sample perpendicular to the MQW layers. In the second experiment, we observe the change in the spontaneous emission lifetime of the MQW caused by the presence of the cavity.

The microcavity was fabricated by the epitaxial growth of both multi quantum well light-emitting active layers and multilayer reflectors on a GaAs substrate. This structure is basically a very short planar Fabry–Perot cavity structure, but with distributed feedback reflectors. The structure is schematically shown in Fig. 1. The active layer consists of a three-period multiple quantum well (MQW) structure having 6.5-nm-thick GaAs wells and $Al_{0.3}Ga_{0.7}As$ barriers of the same thickness, and enclosed by $Al_{0.3}Ga_{0.7}As$ spacer layers. The optical thickness of the active layer is $\lambda/2$. These MQW structures are not intentionally doped, and the background hole density is $\sim 10^{15}$ cm^{-3}. The use of a MQW structure is intended to shift the luminescence peak to shorter wavelengths (~ 830 nm), in order to exclude the possibility of mistakenly detecting the GaAs substrate luminescence (~ 870 nm). One of a pair of reflectors is made from alternating quarter-wavelength layers of AlAs and $Al_{0.3}Ga_{0.7}As$, with 20 pairs of these layers. Based on the layer matrix calculation method,[5] it is estimated that this reflector yields a peak reflectivity $R_1 \sim 0.98$, flat over approximately 20 nm. Half of the sample wafer, hereafter called the "microcavity section" (MCS), is covered by a seven-layer ZnS/SiO_2 upper reflector having a reflectivity $R_2 \sim 0.9$ for the 740–900 nm wavelength region, while showing reflectivity of less than 0.1 for wavelengths shorter than 700 nm. It should be noted that although the whole active layer thickness is $\lambda/2$, the effective cavity length has been estimated to be approximately $\sim 3\lambda$ by a layer matrix simulation of the cavity resonance separation. This is mainly due to penetration of the cavity field into the epitaxial layer reflector. The other half of the wafer, hereafter called the "weak-cavity section" (WCS), has only one ZnS upper layer as a antireflection (AR) coating. Note that there is a weak cavity effect in this section because of the epitaxially grown reflector and the incomplete AR coating.

Calculating the change in spatially integrated spontaneous emission rate is quite difficult with such a distributed feedback structure. However, at least within a small solid angle around the cavity axis, a significant change in the

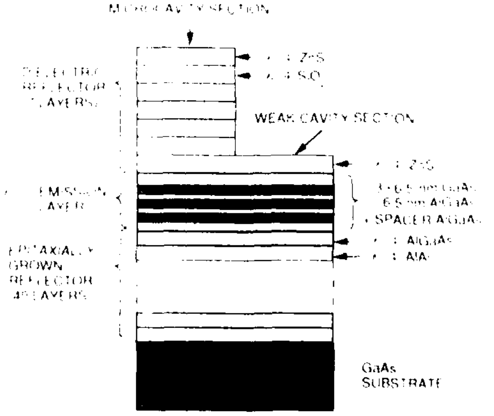

FIG. 1. Schematic of a microcavity MQW structure.

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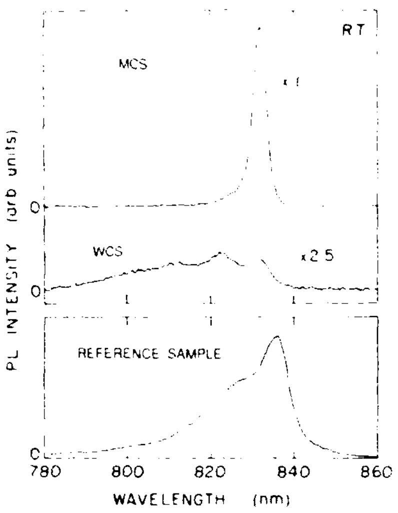

FIG. 2. PL spectra for a microcavity GaAs MQW structure. As a reference a PL spectrum for a MQW without reflectors is also shown. Excitation He-Ne laser light intensity is 1 kW cm^{-2}, with ~24 μm focal spot diameter. PL detection solid angle is ~$10^{-2}\pi$.

emission intensity is expected.[6] When a semiconductor is placed in a Fabry–Perot (FP) microcavity and only one FP mode exists within its emission width, the intensity ratio η for spectrally integrated emission into the cavity axis direction can be expressed as[6]

$$\eta = P(E_0')\Delta E/P(E_0)\Delta P. \qquad (1)$$

where $P(E)$ is the energy-dependent transition rate of the semiconductor at photon energy E. E_0' and E_0 are respectively the photon energies at the cavity resonance peak and at the free-space emission peak, and ΔE and ΔP are respectively the FP mode separation, and the full width at half maximum (FWHM) of $P(E)$. Here we assume that the absorptive loss is negligible. If $E_0' = E_0$, the emission intensity is enhanced by a ratio of $\sim\Delta E/\Delta P$. This shows that the spectrally integrated emission enhancement depends on the cavity mode separation (i.e., the optical thickness of a Fabry–Perot cavity). Note that if $E_0' \neq E_0$ and $P(E_0)/P(E_0') > \Delta E/\Delta P$, the microcavity causes the spontaneous emission into the cavity axis direction to be suppressed instead of enhanced. The electrodynamics of such Fabry–Perot cavities is discussed more fully in Ref. 7.

For both measurements, a small sample including both the MCS and WCS was extracted from a 40-mm-diam wafer. The static PL intensity measurements were carried out using He-Ne laser excitation ($\lambda = 633$ nm). The focal spot diameter on the sample surface is estimated to be ~24 μm. To avoid cracking the coated dielectric layers, all the measurements were carried out at room temperature.

Figure 2 shows the static PL spectra for the sample. The reference spectrum was obtained from a MQW sample without any reflectors. Since this comes from another wafer, its amplitude should not be compared with those from the microcavity sample. (Its peak wavelength is also somewhat longer because the QW layers were slightly thicker.) In the measurement, PL is detected along the axis perpendicular to the sample surface within a solid angle of ~$10^{-2}\pi$. The observed PL spectral width for the MCS is ~4 nm full width at half maximum (FWHM) around the lowest quantized electron–heavy hole transition. The PL spectrum for the WCS is modified by a residual cavity effect. The spectral shapes for both MCS and WCS do not change when the excitation intensity is varied from 1 kW cm^{-2} to ~100 W cm^{-2} (the detection limit for spectra). It should be noted that the MCS and WCS, from which PL data are obtained, are less than 1 mm distant from each other on the wafer in order to assure similarity of the layer thickness and the quality of the MQW.

Integration of the curves shown in Fig. 2 shows that the spectrally integrated PL intensity emitted into the cavity axis direction is increased by a factor of 3.6 by the microcavity. From (1) we estimate an expected enhancement factor of 7–8. Considering the absorption of the MQW, the observed enhancement factor of 3.6 seems to be reasonable.

It is important in these experiments to distinguish between stimulated and spontaneous emission. When the carrier density is less than 10^{18} cm^{-3}, net stimulated emission (stimulated emission rate > stimulated absorption rate) may not occur around the PL peak wavelengths.[8] For our pumping intensity, we estimate the carrier density to be ~10^{18} cm^{-3}. Thus, the light emission observed in the present experiment is due to spontaneous emission. Furthermore, even if the carrier density is increased to 10^{19} cm^{-3}, the gain induced in the MQW is optimistically 10^{2} cm^{-1}, giving a single pass MQW gain of $\sim 4\times10^{-4}$ for the cavity axis direction. This value is much smaller than the mirror transmission loss $1-\sqrt{R_1R_2}\sim0.06$. Finally, the single pass gain for the direction parallel to the MQW is ~0.3 with the present excitation diameter. Accordingly, the effect of stimulated emission is not important at this carrier density.

With samples extracted from other parts of the whole wafer, shifts of the microcavity resonance peak to long wavelengths have been observed. This peak is due to the slight change in the active layer thickness originating from the flux density gradient of the molecular beam during MBE growth. When the resonance peak occurs at a wavelength longer than 840 nm (off-resonance microcavity), the MCS emission intensity into the cavity axis becomes lower than that of the WCS section as expected, i.e., $P(E_0')\Delta E/P(E_0)\Delta P < 1$ in (1).

Thus far, we have discussed changes of the PL intensity in the cavity axis direction. However, the presence of the cavity can also alter the total spontaneous emission rate (i.e., the actual radiative lifetime), analogously to the case of dye molecules encased in thin dielectric layers.[1,9] We have demonstrated these effects with time-resolved PL measurements. In this experiment, an AlGaInP visible diode laser ($\lambda \simeq 660$ nm) excites the sample with a picosecond pulse of light; the decay of the emitted PL is monitored in time using the single photon counting technique.[10] The measurements have also been carried out at room temperature. From the time-resolved PL measurement, the

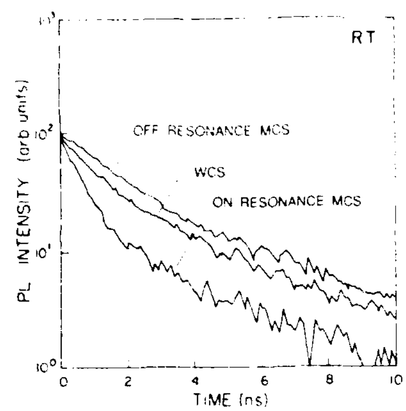

FIG. 3. Temporal variation of the spectrally integrated PL intensity for a GaAs microcavity. The decay times are estimated from the slope of the decay in the initial 2 ns portion of the curve.

nonradiative carrier lifetime of the MQW structure has been determined to be ~ 2 ns at room temperature. This indicates that the well/barrier interfacial recombination velocity is rather large. Although a radiative lifetime change cannot be observed at an initial carrier density lower than 10^{17} cm^{-3} because of the very short nonradiative lifetime, the lifetime difference between the MCS and WCS becomes comparable to the nonradiative case. As explained previously, the contribution of stimulated emission is quite unimportant even at this excitation condition in the present microcavity structure. In Fig. 3, the decay of the spectrally integrated PL intensity is shown for $\sim 10^{18}$ cm^{-3} initial carrier density. The slope of the initial PL decay trace gives decay time constants of ~ 1 ns for the WCS and off-resonant MCS, and ~ 0.6 ns for the on-resonant MCS section. The observed initial decay time τ_f is related to the nonradiative decay time τ_{nr}, and the radiative decay time τ_{rad} by $1/\tau_f = 1/\tau_{nr} + 1/\tau_{rad}$. Although the estimated value of radiative lifetime τ_{rad} sensitively depends on the value of τ_{nr}, using the above relation and the measured nonradiative lifetime $\tau_{nr} \sim 2$ ns, we find radiative lifetimes around 2 ns for the WCS and the off-resonant MCS, and 1 ns for the on-resonant MCS, respectively. The 2 ns time is comparable to previously reported values of radiative lifetimes in samples with carrier densities of 10^{18} cm^{-3} within a factor of 2.[11] The reduction of 1 ns directly reflects the spontaneous emission rate enhancement by the microcavity. Inhibition of the overall emission rate, if any is induced in this structure, is rather small in the present experiment. However, the experimental results demonstrate that an overall enhancement of the spontaneous emission rate is obtainable in the on-resonant MCS compared to the WCS.

In conclusion, our results show for the first time that spontaneous emission alteration is indeed obtainable when GaAs MQWs are incorporated in a planar microcavity. Specifically, the microcavity structure examined here caused both an increase of the spontaneous emission intensity in the cavity axis direction, as well as a change in the overall spontaneous emission lifetime. Although laser oscillation was not observed here because of the high loss cavity, similar alteration in spontaneous emission will certainly occur in the operation of recent surface emitting microcavity laser devices.

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